

# Magnetic Monopole Searches

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Lectures at the 7<sup>th</sup> School on Non-Accelerator Astroparticle Physics,  
ICTP, Trieste, Italy, 26 July - 6 August 2004.

## Abstract

In these lecture notes we discuss the status of the searches for classical Dirac Magnetic Monopoles (MMs) at accelerators, for GUT superheavy MMs in the penetrating cosmic radiation and for Intermediate Mass MMs. Also the searches for nuclearites and Q-balls are considered.

## 1 Introduction

The concept of magnetic monopoles (MMs) goes back to the origin of magnetism. At the beginning of the 19th century there were discussions concerning the magnetic content of matter and the possible existence of isolated magnetic charges. In 1931 Dirac introduced the MM in order to explain the quantization of the electric charge [1]. He established the relation between the elementary electric charge  $e$  and a basic magnetic charge  $g$ :  $eg = n\hbar c/2 = ng_D$ , where  $n$  is an integer,  $n = 1, 2, \dots$ ;  $g_D = \hbar c/2e = 68.5e$  is the unit Dirac charge. The existence of magnetic charges and of magnetic currents would symmetrize in form Maxwell's equations, but the symmetry would not be perfect since  $e \neq g$  (but the couplings could be energy dependent and could merge in a common value at high energies) [2]. There was no prediction for the MM mass; a rough estimate, obtained assuming that the classical monopole radius is equal to the classical electron radius yields  $m_M \simeq \frac{g^2 m_e}{e^2} \simeq n 4700 m_e \simeq n 2.4 \text{ GeV}/c^2$ . From 1931 searches for “classical Dirac monopoles” were carried out at every new accelerator using simple setups, and recently also large collider detectors<sup>3–7</sup>.

Electric charge is naturally quantized in Grand Unified Theories (GUT) of the basic interactions; they imply the existence of *GUT monopoles* with calculable properties. The MMs appear in the Early Universe at the phase transition corresponding to the breaking of the unified group into subgroups, one of which is U(1) [8]. The MM mass is related to the mass of the X, Y carriers of the unified interaction,  $m_M \geq m_X/G$ , where  $G$  is the dimensionless unified coupling constant at energies  $E \simeq m_X$ . If  $m_X \simeq 10^{14} - 10^{15} \text{ GeV}$  and  $G \simeq 0.025$ ,  $m_M > 10^{16} - 10^{17} \text{ GeV}$ . This is an enormous mass: MMs cannot be produced at any man-made accelerator, existing or conceivable. They may have been produced only in the first instants of our Universe.

Larger MM masses are expected if gravity is brought into the unification picture, and in some SuperSymmetric models.

*Multiply charged Intermediate Mass Monopoles* (IMMs) may have been produced in later phase transitions in the Early Universe, when a semisimple gauge group yields a U(1) group [9]. IMMs with  $m_M \sim 10^7 \div 10^{13} \text{ GeV}$  may be accelerated to relativistic velocities in one galactic magnetic field domain. Very energetic IMMs could yield the highest energy cosmic rays [10].

The lowest mass MM is stable, since magnetic charge is conserved like electric charge. Thus the poles produced in the Early Universe should still exist as cosmic relics; their kinetic energy was affected by the Universe expansion and by travel through galactic and intergalactic magnetic fields.

GUT poles are best searched for underground in the penetrating cosmic radiation (CR). IMMs may be searched for at high altitude laboratories.

In this lecture we review the experimental situation on MM searches and briefly discuss the searches for nuclearites [11] and Q-balls [12].

## 2 Properties of magnetic monopoles

The main properties of MMs are obtained from the Dirac relation.

- If  $n = 1$  and the basic electric charge is that of the electron, then the *basic magnetic charge* is  $g_D = \hbar c / 2e = 137e/2$ . The magnetic charge is larger if  $n > 1$  and if the basic electric charge is  $e/3$ .
- In analogy with the fine structure constant,  $\alpha = e^2 / \hbar c \simeq 1/137$ , the *dimensionless magnetic coupling constant* is  $\alpha_g = g_D^2 / \hbar c \simeq 34.25$ ; since it is  $> 1$  perturbative calculations cannot be used.
- *Energy  $W$  acquired in a magnetic field  $B$* :  $W = n g_D B \ell = n 20.5 \text{ keV/G cm}$ . In a coherent galactic-length ( $\ell \simeq 1 \text{ kpc}$ ,  $B \simeq 3 \mu\text{G}$ ), the energy gained by a MM with  $g = g_D$  is  $W \simeq 1.8 \times 10^{11} \text{ GeV}$ . Classical poles and IMMs in the CR may be accelerated to relativistic velocities. GUT poles should have low velocities,  $10^{-4} < \beta < 10^{-1}$ .
- *MMs may be trapped in ferromagnetic materials* by an image force, which could reach values of  $\sim 10 \text{ eV/\AA}$ .
- Electrically charged monopoles (dyons) may arise as quantum-mechanical excitations or as M-p, M-nucleus composites.
- The interaction of a MM magnetic charge with a nuclear magnetic dipole could lead to the formation of a M-nucleus bound system. A monopole-proton bound state may be produced via radiative capture. Monopole-nucleus bound states may exist for nuclei with large gyromagnetic ratios.
- *Energy losses of fast poles*. A fast MM with magnetic charge  $g_D$  and velocity  $v = \beta c$  behaves like an electric charge  $(ze)_{eq} = g_D \beta$ , Fig. 1.
- *Energy losses of slow poles* ( $10^{-4} < \beta < 10^{-2}$ ) may be due to ionization or excitation of atoms and molecules of the medium ("electronic" energy loss) or to recoiling atoms or nuclei ("atomic" or "nuclear" energy loss). Electronic energy loss predominates for  $\beta > 10^{-3}$ .
- *Energy losses at very low velocities*. MMs with  $v < 10^{-4}c$  may lose energy in elastic collisions with atoms or with nuclei. The energy is released to the medium in the form of elastic vibrations and/or infra-red radiation [13].

Fig. 1 shows the energy loss in liquid hydrogen of a  $g = g_D$  MM vs  $\beta$  [4].

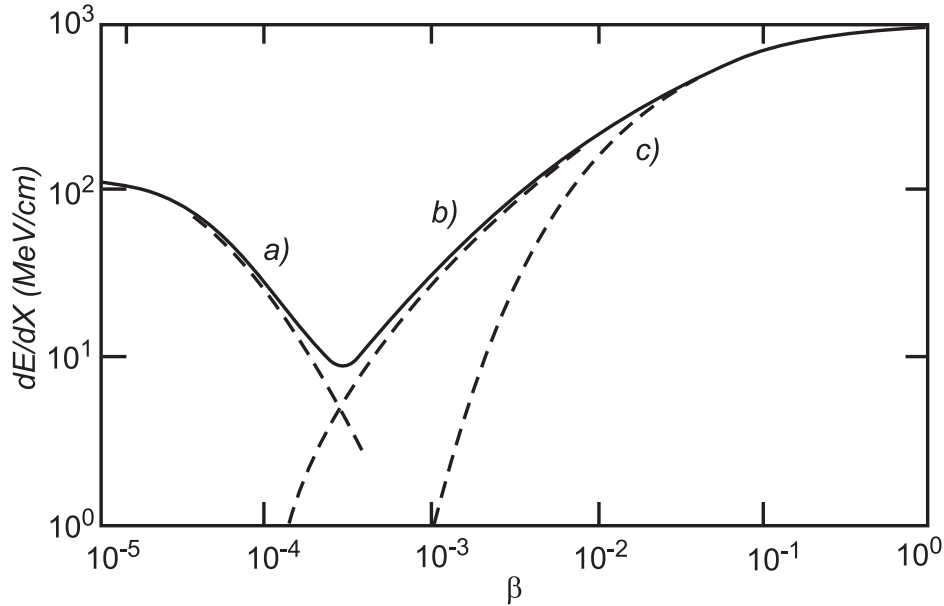


Figure 1: The energy losses, in MeV/cm, of  $g = g_D$  MMs in liquid hydrogen vs  $\beta$ . Curve a) corresponds to elastic monopole-hydrogen atom scattering; curve b) to interactions with level crossings; curve c) describes the ionization energy loss.

- *Energy loss of MMs in celestial bodies*. For  $\beta < 10^{-4}$  the  $dE/dx$  in the Earth is due to pole-atom elastic scattering, eddy currents, and nuclear stopping power. MMs may be stopped by celestial

bodies if they have:

Moon:  $\beta \leq 5 \times 10^{-5}$ , Earth:  $\beta \leq 10^{-4}$ , Sun:  $\beta \leq 10^{-3}$ .

### 3 Monopole detectors

Monopole detectors are based on MM properties given by Dirac's relation.

- *Superconducting induction devices are sensitive to MMs of any velocity* [3]. A moving MM induces in a ring an electromotive force and a current change ( $\Delta i$ ). For a coil with  $N$  turns and inductance  $L$ ,  $\Delta i = 4\pi N n g_D / L = 2\Delta i_o$ , where  $\Delta i_o$  is the current change corresponding to a change of one unit of the flux quantum of superconductivity. This method of detection is based only on the long-range electromagnetic interaction between the magnetic charge and the macroscopic quantum state of a superconducting ring.

- *Scintillation counters* for MMs have a threshold  $\beta \sim 10^{-4}$ , above which the light signal is larger than that of a minimum ionizing particle [13, 14].

- *Gaseous detectors* of various types have been used. MACRO used a gas mixture of 73% helium and 27% n-pentane [14]. This allows exploitation of the Drell [15] and Penning effects [3]: a MM leaves a helium atom in a metastable state ( $\text{He}^*$ ) with an excitation energy of  $\simeq 20$  eV. The ionization potential of n-pentane is  $\simeq 10$  eV; the excited energy of the  $\text{He}^*$  is converted into ionization of the n-pentane molecule (Pening effect).

- *Nuclear track detectors (NTDs)*. The formation of an etchable track in a NTD is related to the Restricted Energy Loss (REL), the fraction of the energy loss localized in a cylindrical region of 10 nm diameter around the particle trajectory. It was shown that both the electronic and the nuclear energy losses are effective in producing etchable tracks in the CR39 NTD which has a threshold at  $z/\beta \simeq 5$  [16]; it is the most sensitive NTD and it allows to search for MMs with  $g = g_D$  for  $\beta$  around  $10^{-4}$  and  $> 10^{-3}$ , the whole  $\beta$ -range of  $4 \times 10^{-5} < \beta < 1$  for MMs with  $g \geq 2g_D$  [13]. The Lexan and Makrofol polycarbonates are sensitive for  $z/\beta \geq 50$  [17].

### 4 “Classical Dirac monopoles”

- *Accelerator searches*. If MMs are produced at high-energy accelerators, they would be relativistic and would ionize heavily. Examples of *direct searches* are the experiments performed with scintillators or NTDs. Experiments at the Fermilab  $\bar{p}p$  collider established cross section limits of  $\sim 2 \times 10^{-34} \text{ cm}^2$  for MMs with  $m_M < 850 \text{ GeV}$  [18]. Searches at  $e^+e^-$  colliders excluded masses up to 45 GeV and later in the 45-102 GeV range ( $\sigma < 5 \times 10^{-37} \text{ cm}^2$ ). Recently few high energy general purpose detectors used some subdetectors to search for Dirac MMs [7].

Fig. 2 summarizes the cross section limits vs MM mass obtained by direct and indirect experiments (solid lines and dashed lines) at the Fermilab  $\bar{p}p$  collider,  $e^+e^-$  colliders, the ISR  $pp$  collider [4]. Most searches are sensitive to poles with magnetic charges  $g = n g_D / q$  with  $0.5 < n < 5$ .

Examples of indirect searches are those performed at the CERN SPS and at Fermilab: the protons interacted in ferromagnetic targets, later the targets were placed in front of a superconducting solenoid with a field  $B > 100 \text{ kG}$ , large enough to extract and accelerate the MMs, to be detected in scintillators and in NTD sheets [3]. An indirect experiment performed at the  $\bar{p}p$  Tevatron collider, assumed that produced MMs could stop, be trapped and bound in the matter surrounding a collision region [5]. Small Be and Al samples were passed through the 10 cm diameter bore of two superconducting coils, and the induced charge measured by SQUIDS. Limits  $m_M > 285 \text{ GeV}$  were published for  $g = g_D$  poles. It is difficult to establish the validity of the hypotheses made to interpret these results.

- *Multi- $\gamma$  events*. Five peculiar photon showers found in emulsion plates exposed to high-altitude CRs, are characterized by an energetic narrow cone of tens of photons, without any incident charged particle [19]. The total energy of the photons is  $\sim 10^{11} \text{ GeV}$ . The small radial spread of photons suggested a c.m.  $\gamma = (1 - \beta^2)^{-1/2} > 10^3$ . The energies of the photons are too small to have  $\pi^0$  decays as their source. One possible explanation: a high-energy  $\gamma$ -ray, with energy  $> 10^{12} \text{ eV}$ , produced a pole-antipole pair, which suffered bremsstrahlung and annihilation producing the final multi- $\gamma$  events. Searches for multi- $\gamma$  events were performed in  $pp$  collisions at the ISR at  $\sqrt{s} = 53 \text{ GeV}$ , at the  $\bar{p}p$  1.8 TeV collider and in  $e^+e^-$  collisions at LEP (Fig. 2). The D0 experiment searched for  $\gamma$

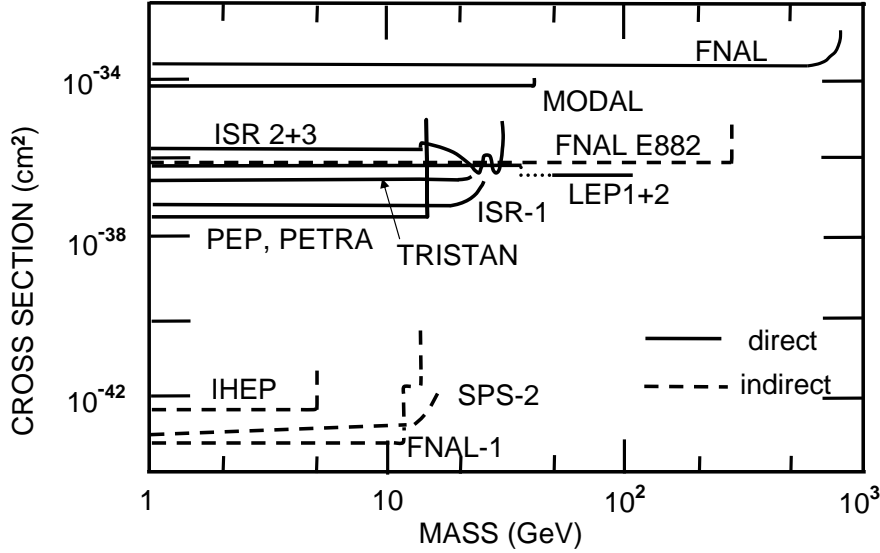


Figure 2: Classical Dirac MMS cross section upper limits vs MM mass obtained from direct accelerator searches (solid lines) and indirect searches (dashed lines).

pairs with high transverse energies; virtual pointlike MMs may rescatter pairs of nearly real photons into the final state via a box monopole diagram; they set a 95% CL limit of 870 GeV [5]. At LEP the L3 coll. searched for  $Z \rightarrow \gamma\gamma\gamma$  events; no deviation from QED predictions was observed, setting a 95% CL limit of 510 GeV [5]. Many authors studied the effects from virtual monopole loops [2, 20]. The authors of Ref. [6] criticized the underlying theory and believe that no significant limit can be obtained from present experiments.

- *Searches in bulk matter.* Classical MMs could be produced by CRs and could stop at the Earth surface, where they may be trapped in ferromagnetic materials. Bulk matter searches used hundreds of kg of material, including meteorites, schists, ferromanganese nodules, iron ore and others. A superconducting coil through which the material was passed, yielded a monopole/nucleon ratio in the samples  $< 1.2 \times 10^{-29}$  at 90% CL [3].

Ruzicka and Zrellov summarized all searches for classical poles performed before 1980 [21]. A more recent bibliography is given in Ref. [22]. Possible effects arising from low mass MMs have been reported in Ref. [23].

## 5 GUT monopoles

As already stated, GUT theories of the electroweak and strong interactions predict the existence of superheavy MMs produced in the Early Universe (EU) when the GUT gauge group breaks into separate groups, one of which is  $U(1)$ . Assuming that the GUT group is  $SU(5)$  (which is excluded by proton decay experiments) one should have the following transitions:

$$SU(5) \xrightarrow[10^{-35}s]{10^{15} \text{ GeV}} SU(3)_C \times [SU(2)_L \times U(1)_Y] \xrightarrow[10^{-9}s]{10^2 \text{ GeV}} SU(3)_C \times U(1)_{EM} \quad (1)$$

MMs would be generated as topological point defects in the GUT phase transition, about one pole for each causal domain. In the standard cosmology this leads to too many poles (the monopole problem). Inflation would defer the GUT phase transition after large supercooling; in its simplest version the number of generated MMs would be very small. However the flux depends critically on several parameters, like the pole mass, the reheating temperature, etc. If the reheating temperature is large enough one would have MMs produced in high energy collisions, like  $e^+e^- \rightarrow MM$ .

Fig. 3 shows the structure of a GUT MM: a very small core, an electroweak region, a confinement

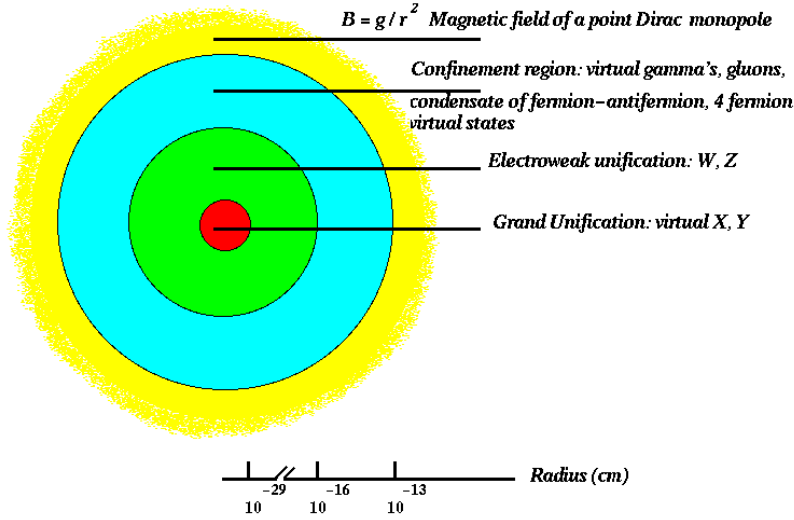


Figure 3: Structure of a GUT pole. The 4 regions correspond to: (i) Grand Unification ( $r \sim 10^{-29}$  cm; inside this core one finds virtual  $X, Y$  particles); (ii) electroweak unification ( $r \sim 10^{-16}$  cm; inside one finds virtual  $W^\pm$  and  $Z^0$ ); (iii) confinement region ( $r \sim 10^{-13}$  cm; inside one finds virtual  $\gamma$ , gluons, fermion-antifermion pairs and possibly 4-fermion virtual states); (iv) for  $r > \text{few fm}$  one has the field of a point magnetic charge.

region, a fermion-antifermion condensate (which may contain 4-fermion baryon-number-violating terms); for  $r \geq 3 \text{ fm}$  it behaves as a point particle generating a field  $B = g/r^2$  [24].

A flux of cosmic GUT MMs may reach the Earth with a velocity spectrum in the range  $4 \times 10^{-5} < \beta < 0.1$ , with possible peaks corresponding to the escape velocities from the Earth, the Sun and the Galaxy. Searches for such MMs in the CR performed with superconducting induction devices yielded a combined 90% CL limit of  $2 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ , independent of  $\beta$  [4]. Direct searches were performed above ground and underground <sup>4,25-27</sup>. MACRO performed a search with different types of detectors (liquid scintillators, limited streamer tubes and NTDs) with an acceptance of  $\sim 10,000 \text{ m}^2 \text{ sr}$  for an isotropic flux. No MM was detected; the 90% CL flux limits, shown in Fig. 4 vs  $\beta$  for  $g = g_D$ , are at the level of  $1.4 \times 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$  for  $\beta > 4 \times 10^{-5}$  [25]. The figure shows also the limits from the Ohya [26], Baksan, Baikal, and AMANDA experiments [27].

The interaction of the GUT monopole core with a nucleon can lead to a reaction in which the nucleon decays (monopole catalysis of nucleon decay), f. e.  $M + p \rightarrow M + e^+ + \pi^0$ . The cross section for this process is very small, of the order of magnitude of the core size; but the catalysis process could proceed via the Rubakov-Callan mechanism with a  $\sigma$  of the order of the strong interaction cross section [28]. MACRO performed a dedicated search for nucleon decays induced by the passage of a GUT pole in the streamer tube system. The flux limits obtained,  $3 - 8 \times 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ , depend on the MM velocity and on the catalysis cross section [29]. Previous limits were at levels  $10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$  [29], except the Baikal limit which is  $6 \times 10^{-17} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$  for  $\beta \simeq 10^{-5}$  [27].

Indirect GUT MM searches used ancient mica, which has a high threshold. It is assumed that a pole passing through the Earth captures an Al nucleus and drags it through subterranean mica causing a trail of lattice defects, which survive as long as the mica is not reheated. Only small sheets were analyzed ( $13.5$  and  $18 \text{ cm}^2$ ), but should have been recording tracks for  $4 \div 9 \times 10^8$  years. The flux limits are  $10^{-17} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$  for  $10^{-4} < \beta < 10^{-3}$  [30]. There are reasons why these indirect experiments might not be sensitive: if MMs have a positive electric charge or protons attached, then Coulomb repulsion could prevent capture of heavy nuclei.

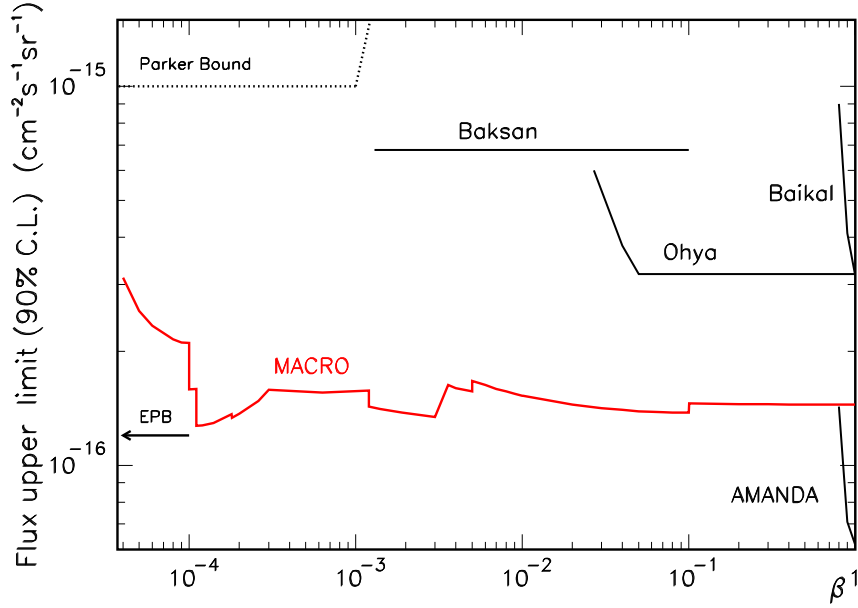


Figure 4: The 90% CL MACRO direct upper limits vs  $\beta$  for GUT  $g = g_D$  poles in the penetrating CR, and direct limits from other experiments (see text).

## 6 Cosmological and astrophysical bounds

Rough upper limits for a GUT monopole flux in the CR were obtained on the basis of cosmological and astrophysical considerations.

- *Limit from the mass density of the universe:* it is obtained requiring that the present MM mass density be smaller than the critical density  $\rho_c$  of the universe. For  $m_M \simeq 10^{17}$  GeV one has the limit:  $F = \frac{v_M c}{4\pi} \beta < 3 \times 10^{-12} h_0^2 \beta$  ( $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ ). It is valid for poles uniformly distributed in the universe. If poles are clustered in galaxies the limit is larger [3].

- *Limit from the galactic magnetic field (Parker limit).* The  $\sim 3 \mu\text{G}$  magnetic field in our Galaxy is probably due to the non-uniform rotation of the Galaxy, which generates a field with a time-scale of the order of the rotation period of the Galaxy ( $\tau \sim 10^8$  yr). An upper bound for the MM flux is obtained by requiring that the kinetic energy gained per unit time by MMs be less than the magnetic energy generated by the dynamo effect:  $F < 10^{-15} \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$  [31]; taking into account the almost chaotic nature of the field, with domains of  $\ell \sim 1$  kpc, the limit becomes mass dependent [31]. An extended “Parker bound”, obtained by considering the survival of an early seed field [32], yields  $F \leq 1.2 \times 10^{-16} (m_M/10^{17} \text{ GeV}) \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ .

- *Limit from the intergalactic (IG) magnetic field.* If  $B_{IG} \sim 3 \times 10^{-8}$  G with a regeneration time  $\tau_{IG} \sim 10^9$  y, a more stringent bound is obtained; the limit is less reliable because the IG field is less known.

- *Limits from peculiar  $A_4$  stars and from pulsars* may be stringent, but the assumptions made are not clear (see the pulsar PSR 1937+214) [3, 4].

## 7 Intermediate mass magnetic monopoles

IMMs may appear as topological point defects at a later time in the Early Universe; f.e. the  $\text{SO}(10)$  GUT group would not yield directly a  $\text{U}(1)$  group

$$\text{SO}(10) \xrightarrow[10^{-35} \text{ s}]{10^{15} \text{ GeV}} \text{SU}(4) \times \text{SU}(2) \times \text{SU}(2) \xrightarrow[10^{-23} \text{ s}]{10^9 \text{ GeV}} \text{SU}(3) \times \text{SU}(2) \times \text{U}(1) \quad (2)$$

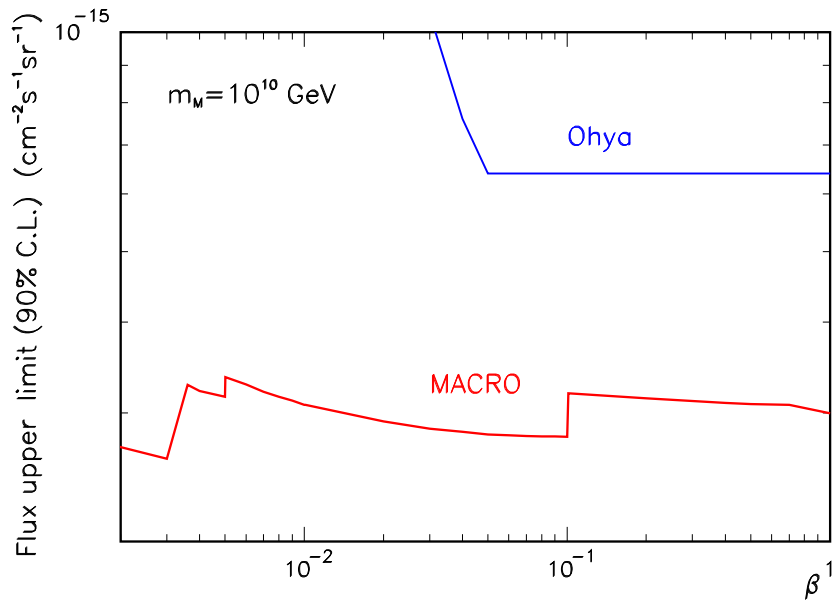


Figure 5: Experimental 90% CL upper limits for a flux of IMM with mass  $m_M = 10^{10}$  GeV plotted versus  $\beta$ .

This would lead to MMs with masses of  $\sim 10^{10}$  GeV; they would survive inflation, be stable, “doubly charged” ( $g = 2g_D$ ) and do not catalyze nucleon decay [9]. The structure of an IMM would be similar to that of a GUT MM, but the core would be larger (since  $R \sim 1/m_M$ ) and the outer cloud would not contain 4-fermion baryon-number-violating terms.

Relativistic IMM,  $10^7 < m_M < 10^{13}$  GeV, could be present in the cosmic radiation, could be accelerated to large  $\gamma$  in one coherent domain of the galactic field. Thus one would have to look for  $\beta \geq 0.1$  MMs.

Detectors at the Earth surface could detect MMs coming from above if they have  $m_M > 10^5 - 10^6$  GeV [13]; lower mass MMs may be searched for with detectors located at high mountain altitudes, balloons and satellites.

Few experimental results are available. Fig. 5 shows the situation on the flux upper limits for IMM [4]. The Cherenkov neutrino telescopes under ice and underwater are sensitive to fast ( $\gamma \gg 1$ ) MMs coming from above.

The SLIM experiment, which searches for IMM with NTDs at the Chacaltaya high altitude lab (5290 m a.s.l.) [33], is sensitive to  $g = 2g_D$  MMs in the whole range  $4 \times 10^{-5} < \beta < 1$ .

## 8 Nuclearites and Q-balls

Strange Quark Matter (SQM) should consist of aggregates of  $u$ ,  $d$  and  $s$  quarks in almost equal proportions; the number of  $s$  quarks should be lower than the number of  $u$  or  $d$  quarks and the SQM should have a positive integer charge. The overall neutrality of SMQ is ensured by an electron cloud which surrounds it, forming a sort of atom (see Fig. 6). SQM should have a constant density  $\rho_N = M_N/V_N \simeq 3.5 \times 10^{14}$  g cm $^{-3}$ , larger than that of atomic nuclei, and it should be stable for all baryon numbers in the range between ordinary heavy nuclei and neutron stars ( $A \sim 10^{57}$ ). Lumps of SQM with baryon number  $A < 10^6 - 10^7$  are usually called “strangelets”; the word “nuclearite” was introduced to indicate large lumps of SQM which could be present in the CR [11]. SQM lumps could have been produced shortly after the Big Bang and may have survived as remnants; they could also appear in violent astrophysical processes, such as in neutron star collisions. SQM could contribute to the cold dark matter. The main energy loss mechanism for low velocity nuclearites is elastic or

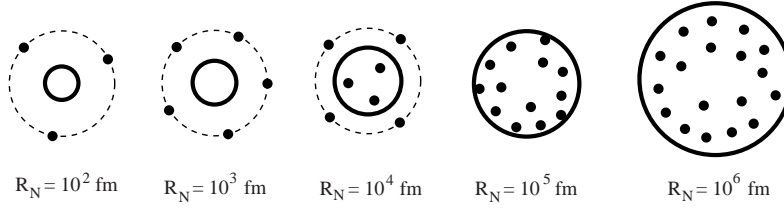


Figure 6: Nuclearite structure. Dimensions of the quark bag (radius  $R_N$ ) and of the core+electron system; the black points are the electrons (the border of the core + electron cloud for small masses is indicated by the dashed lines). For masses smaller than  $10^9$  GeV, the electrons are outside the quark bag, the core+electron system has size of  $\sim 10^5$  fm; for  $10^9 < M_N < 10^{15}$  GeV the  $e^-$  are partially inside the core, for  $M_N > 10^{15}$  GeV all electrons are inside the core.

quasi-elastic collisions with the ambient atoms. The energy loss is large; therefore nuclearites should be easily detected in scintillators and CR39 NTDs [34]. Nuclearites should have typical galactic velocities,  $\beta \sim 10^{-3}$ , and for masses larger than 0.1 g could traverse the earth. Most nuclearite searches were obtained as byproducts of CR MM searches; the flux limits are similar to those for MMs.

The most relevant direct flux limits for nuclearites come from three large area experiments: the first two use CR39 NTDs; one experiment was performed at mountain altitude (Mt. Norikura at 2770 m a.s.l.) [35], the 2nd at the depth of  $10^4$  g  $\text{cm}^{-2}$  in the Ohya mine [26]; the third experiment, MACRO, at an average depth of 3700 hg  $\text{cm}^{-2}$ , used liquid scintillators besides NTDs [36]. A 4th experiment (SLIM) is deployed at high altitudes. Indirect searches with old mica samples could yield the lowest limits, but they are affected by several uncertainties. Some exotic cosmic ray events were interpreted as due to incident nuclearites, f. e. the “Centauro” events and the anomalous massive particles, but the interpretation is not unique [37]. Supermassive nuclearites ( $M \sim 1$  ton) passing through Earth could induce epiliner earthquakes [11, 38]. Fig. 7 shows a compilation of limits for a flux of downgoing nuclearites compared with the dark matter (DM) limit, assuming a velocity at ground level  $\beta = 10^{-3}$ , corresponding to nuclearites of galactic or extragalactic origin. The MACRO limit is extended above the DM bound to show the transition to an isotropic flux for  $M_n > 0.1$  g ( $\sim 10^{23}$  GeV). Some possible positive indications are discussed in Ref. [37].

*Q-balls* should be aggregates of squarks  $\tilde{q}$ , sleptons  $\tilde{l}$  and Higgs fields [12]. The scalar condensate inside a Q-ball core has a global baryon number  $Q$  (and may be also a lepton number). Protons, neutrons and may be electrons could be absorbed in the condensate. There could exist neutral and charged Q-balls. Supersymmetric Electrically Neutral Solitons (SENS) are generally massive and may catalyse proton decay. SENS may obtain a positive electric charge absorbing a proton in their interactions with matter yielding SECS (Supersymmetric Electrically Charged Solitons), which have a core electric charge, have generally lower masses and the Coulomb barrier could prevent the capture of nuclei. SECS have only integer charges because they are color singlets. A SENS which enters the earth atmosphere could absorb a nitrogen nucleus which would give it the positive charge of +7 (SECS with  $z = 7$ ). Other nuclear absorptions are prevented by Coulomb repulsion. If the Q-ball can absorb electrons at the same rate as protons, the positive charge of the absorbed nucleus may be neutralized by the charge of absorbed electrons. If, instead, the absorption of electrons is slow or impossible, the Q-ball carries a positive electric charge after the capture of the first nucleus in the atmosphere. Q-balls may be cold DM candidates. SECS with  $\beta \simeq 10^{-3}$  and  $M_Q < 10^{13}$  GeV could reach an underground detector from above, SENS also from below. SENS may be detected by their continuous emission of charged pions (energy loss  $\sim 100$  GeV  $\text{g}^{-1}\text{cm}^2$ ), SECS may be detected by scintillators, NTDs and ionization detectors.

Note that we did not consider here the possibility of strongly interacting, colored, MMs, nuclearites [41] and Q-balls.



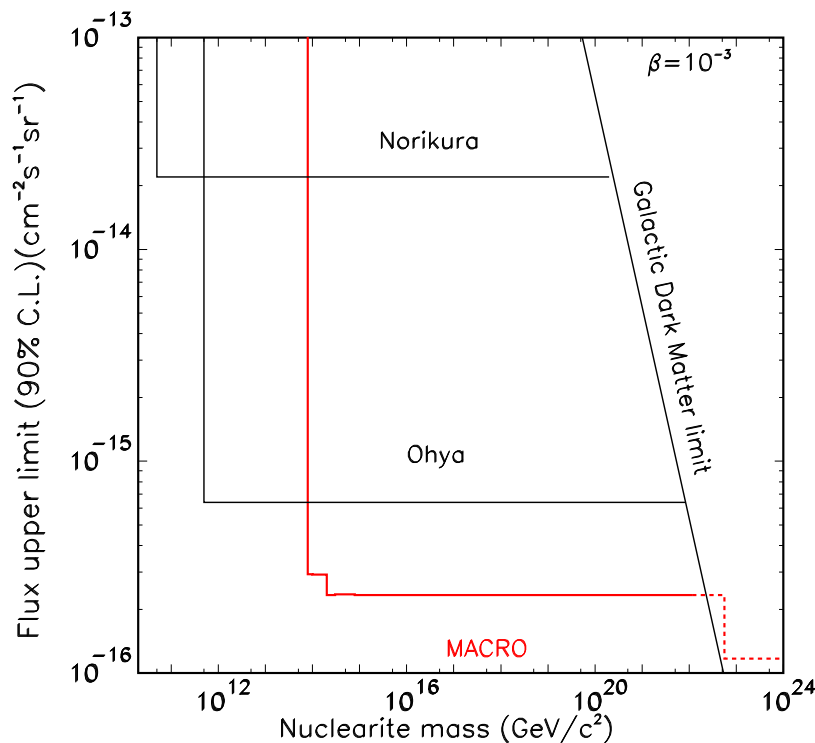


Figure 7: 90% CL flux upper limits versus mass for nuclearites with  $\beta = 10^{-3}$  at ground level. These nuclearites could have galactic or extragalactic origin. The limits are from Refs. <sup>26,35,36</sup>.

## 9 Conclusions. Outlook

Direct and indirect accelerator searches for classical Dirac MMs placed limits at the level  $m_M > 850$  GeV with cross section upper values as shown in Fig. 2. Future improvements may come from experiments at the LHC [42].

Many searches were performed for GUT poles in the penetrating cosmic radiation. The 90% CL flux limits are at  $\sim 1.4 \times 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$  for  $\beta \geq 4 \times 10^{-5}$ . It may be difficult to do much better since one would require refined detectors of considerably larger areas.

Present limits on Intermediate Mass Monopoles with high  $\beta$  are relatively poor. Experiments at high altitudes and at neutrino telescopes should improve the situation. In particular stringent limits may be obtained by large neutrino telescopes for IMMs with  $\beta > 0.5$  coming from above.

As a byproduct of GUT MM searches some experiments obtained stringent limits on nuclearites and on Q-balls. Future experiments at neutrino telescopes and at high altitudes should perform searches for nuclearites and Q-balls of smaller masses.

## 10 Acknowledgements

We acknowledge the cooperation of many colleagues, in particular S. Cecchini, M. Cozzi, M. Giorgini, G. Mandrioli, S. Manzoor, V. Popa, M. Spurio, and others. We thank ms. Giulia Grandi for typing the manuscript.

## References

- [1] P.A.M. Dirac, Proc. R. Soc. London 133(1931)60; Phys. Rev. 74(1948)817.

- [2] A. De Rujula, Nucl. Phys. B435(1995)257.
- [3] G. Giacomelli, Riv. Nuovo Cimento 7(1984)N.12, 1.
- [4] G. Giacomelli et al. hep-ex/011209; hep-ex/0302011; hep-ex/0211035.
- [5] G.R. Kalbfleisch, Phys. Rev. Lett. 85(2000)5292. K.A.Milton et al. hep-ex/0009003. B. Abbott et al., Phys. Rev. Lett. 81(1998)524. M. Acciarri et al., Phys. Lett. B345(1995)609.
- [6] L. Gamberg et al., hep-ph/9906526.
- [7] Private communication by M. Cozzi.  
K. Kinoshita et al., Phys. Rev. D46(1992)R881.
- [8] G.'t Hooft, Nucl. Phys. B29(1974)276. A.M. Polyakov, JETP Lett. 20(1974)194. N.S. Craigie et al., Theory and Detection of MMs in Gauge Theories, World Scientific, Singapore (1986).
- [9] G. Lazarides et al., Phys. Rev. Lett. 58(1987)1707.  
T. W. Kephart and Q. Shafi, Phys. Lett. B520(2001)313.
- [10] P. Bhattacharjee and G. Sigl, Phys. Rept. 327(2000)109 and refs. therein.
- [11] E. Witten, Phys. Rev. D30(1984)272.  
A. De Rujula and S. Glashow, Nature 31(1984)272.
- [12] S. Coleman, Nucl. Phys. B262(1985)293.  
A. Kusenko and A. Shaposhnikov, Phys. Lett. B418(1998)46.
- [13] J. Derkaoui et al., Astrop. Phys. 9(1998)173; Astrop. Phys. 9(1999)339.
- [14] S. Ahlen et al., Phys. Rev. Lett. 72(1994)608. M. Ambrosio et al., Astrop. Phys. 6(1997)113; Nucl. Instr. Meth. A486(2002)663; Astrop. Phys. 4(1995)33; Astrop. Phys. 18(2002)27.
- [15] G.F. Drell et al., Nucl. Phys. B209(1982)45.
- [16] S. Cecchini et al., Nuovo Cim. A109(1996)1119.
- [17] S. Cecchini et al., 22th ICNTS, Barcelona, Spain, 2004, hep-ex/0503003; hep-ex/0502034.
- [18] M. Bertani et al., Europhys. Lett. 12(1990)613.
- [19] M. Schein et al., Phys. Rev. 99(1955)643.
- [20] I. F. Ginzburg and A. Schiller, Phys. Rev. D60(1999)075016.
- [21] J. Ruzicka and V.P. Zrelov JINR-1-2-80-850(1980).
- [22] G. Giacomelli et al., hep-ex/0005041.
- [23] V.A. Skvortsov et al., 29th EPS Plasma Conf., ECA 26B, D-5.013 (2002).
- [24] D. Bakari et al., hep-ex/0004019.
- [25] M. Ambrosio et al., MACRO Coll., Eur. Phys. J. C25(2002)511; Phys. Lett. B406(1997)249; Phys. Rev. Lett. 72(1994)608.
- [26] S. Orito et al. (“Ohya”), Phys. Rev. Lett. 66(1991)1951.
- [27] E.N. Alexeyev et al. (“Baksan”), 21<sup>st</sup> ICRC 10(1990)83.  
V.A. Balkanov et al. (“Baikal”) Nucl. Phys. B(Proc. Suppl.) 91(2001)438.  
P.Niessen et al., 27<sup>st</sup> ICRC 3(2001)1496.

- [28] V.A. Rubakov, JETP Lett. B219(1981)644.  
G.G. Callan, Phys. Rev. D26(1982)2058.
- [29] M. Ambrosio et al., Eur. Phys. J. C26(2002)163.
- [30] P. B. Price, Phys. Rev. D38(1988)3813.  
D. Ghosh and S. Chatterjea, Europhys. Lett. 12(1990)25.
- [31] E.N. Parker, Ap. J. 160(1970)383.  
M.S. Turner et al., Phys. Rev. D26(1982)1296.
- [32] F.C. Adams et al., Phys. Rev. Lett. 70(1993)2511.
- [33] D. Bakari et al., hep-ex/0003028. S. Cecchini et al. 28<sup>st</sup> ICRC 3(2003)1657; Nucl. Phys. B(Proc. Suppl.)138(2005)529.
- [34] M. Ambrosio et al., Eur. Phys. J. C13(2000)453.
- [35] S. Nakamura et al., Phys. Lett. B263(1991)529.
- [36] G. Giacomelli, hep-ex/0210021.
- [37] M. Rybczynski et al., hep-ph/0410064
- [38] D. P. Anderson et al., astro-ph/0205089
- [39] D. Bakari et al., Astrop. Phys. 15(2001)137.
- [40] J. Arafune et al., hep-ph/0005103.
- [41] S.D. Wick et al., astro-ph/0001233.
- [42] Proposal MOEDAL at the LHC, CERN/LHCC 98-5.